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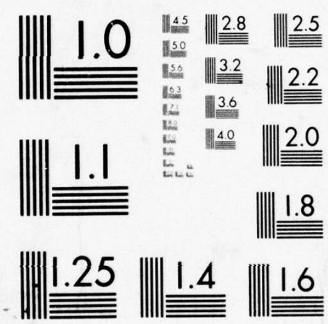
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ON THE IMPORTANCE OF PROGRAM INTELLIGENCE TO ADVANCED AUTOMATION IN FLIGHT OPERATIONS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
COORDINATED SCIENCE LABORATORY
URBANA, ILLINOIS 61801

APRIL 1977

TECHNICAL REPORT AFAL-TR-77-20
FINAL REPORT FOR PERIOD 7/23/73-5/22/76

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AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This technical report has been reviewed and is approved for publication.

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In today's sophisticated aircraft, much emphasis has been placed on the acquiring of and the displaying to the pilot an ever increasing amount of information obtained during flight missions. This has resulted in increased workloads for the pilot which force him to evaluate highly complex sets of input data, to decide upon courses of action, and then to implement those actions in minimal times. Such a situation is seen as undesirable because it increases the pilot's chances for making error which consequently lowers the probability of mission success.

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In order to overcome this undesirable situation, it is argued that a special purpose computer system can provide intelligently evaluated decisions which would reduce the pilot's workload and, therefore, his error rate. Supported by such a computer system, the pilot can then function as a system manager rather than a system component. Up until now, automated systems developed to solve this problem do not adequately handle critical circumstances during times of high workload when the attention of the pilot must be given to numerous tasks. Such conventional automation systems tend to present even larger amounts of data to the pilot and to require him to key in requests for specific information. Whereas they tend to lower workloads during such non-critical times as when cruising, they tend to increase workloads during such critical times as close combat. For example, while a scanning motion on a visual display would normally give the pilot a general idea of the state of his plane, a similar scan with time-shared display would normally require him to key in several requests by hand, a task more difficult and time-consuming for him and which consequently adds to his workload.

In order to continuously provide low workloads and, hence, more safety for the pilot, his crew and the aircraft itself, the Coordinated Science Laboratory has developed a system which relieves the pilot of having to deal with many situations which would detract from his overall mission goals. This intelligent, computer-aided decision making system (CADM) works cooperatively with the pilot in order to ensure the safety of the aircraft and its crew, thereby allowing the accomplishment of successful missions.

PREFACE

This final report describes research performed conjointly by the Coordinated Science Laboratory and the Avionics Research Laboratory at the University of Illinois. The research effort investigated and demonstrated applications of programmed intelligence in flight operations. The work was performed for the System Avionics Division of the Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio on Contract Number F33615-73-C-1238 during the period July 23, 1973 to May 22 1976.

ABSTRACT

In today's sophisticated aircraft, much emphasis has been placed on the acquiring of and the displaying to the pilot an ever increasing amount of information obtained during flight missions. This has resulted in increased workloads for the pilot which force him to evaluate highly complex sets of input data, to decide upon courses of action, and then to implement those actions in minimal times. Such a situation is seen as undesirable because it increases the pilot's chances for making errors which consequently lowers the probability of mission success.

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SECTION I

INTRODUCTION

In today's sophisticated aircraft, much emphasis has been placed on the acquiring of and the displaying to the pilot an ever increasing amount of information obtained during flight missions. This has resulted in increased workloads for the pilot which force him to evaluate highly complex sets of input data, to decide upon courses of action, and then to implement those actions in minimal times. Such a situation is seen as undesirable because it increases the pilot's chances for making errors which consequently lowers the probability of mission success.

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1.1 The CADM System

The computer-aided decision making system (CADM) was designed to handle a broad class of complex problems in a real world problem solving domain. The CADM system which was implemented operates to correct and compensate for midflight failures of aircraft components that require degraded mode operation. These failures may occur in the fuel system and in the electrical system. In doing so, the system constructs correction and monitoring procedures which specifically fit the airplane configuration, the component allocation and the failure.

These general correction procedures allow the system to be essentially airplane independent. However, in order to demonstrate these concepts the system implemented at the Coordinated Science Laboratory corrects and compensates for failures in the fuel and electrical systems of a twin engine jet aircraft. In addition, it allows real time interaction with the airplane models and pilot.

1.1.1 System Goals for CADM

Within this domain, certain goals of performance were established. These goals are 1) to instill CADM with the ability to handle multiple failures, 2) to establish a good working relationship between CADM and the pilot, and 3) to make the system as general as possible.

1.1.1.1 CADM Failure Handling

The handling of failures involves not only the cases in which failures occur singly, but also those cases in which multiple failures occur simultaneously, as well as those cases in which failures occur while CADM is monitoring the progress of on-going correction procedures. In order to accomplish this, CADM oversees the allocation of aircraft components by means of a variable priority structure which relates the relative importance of correcting a class of failures to the mission profile and available equipment.

1.1.1.2 The Pilot-CADM Relationship

CADM's overriding concern is that the pilot must be able to assume full control over the airplane's capabilities in order to successfully carry out the mission. For this reason, CADM must be careful not to undo pilot actions, and must, therefore, continuously monitor the pilot's actions. In order to keep the pilot informed of what CADM is doing and is trying to accomplish, CADM provides the pilot with information concerning CADM detections, corrections, and perceptions of failures within the aircraft. However, the CADM system attempts to keep from burdening the pilot with excessive or extraneous information. The information is available if the pilot wishes it, but it is not forced upon him.

1.1.1.3 The Generality of CADM

In attempting to maintain generality for the CADM system, the techniques used for correcting failures are not directed toward a fixed class of errors on a specific airplane type. Accordingly, the system developed introduces generality into two areas. First, the airplane model is treated as factual data rather than as explicit coding into the program. Second, the correction procedures are generalized to model component and instrument types rather than to specific switches or dials, and are implemented with knowledge of how these component types operate and affect the operation of the airplane.

1.1.2 CADM System Elements

The overall system is depicted in Figure 1. As new data is received from the common data base, the information is automatically processed by special purpose procedures (called DEMONS).

The DEMON system allows effective monitoring of on-going correction procedures. Using the DEMON system, the pilot's actions can be monitored in order to allow CADM to operate without interfering with the pilot's actions. DEMONs also allow the re-evaluation of on-going correction procedures in order to upgrade them to more efficient ones, or in the case of failure, to use system maintained histories to construct alternate correction procedures in order to perform error recovery.

A check is made to determine if failures exist, and if so, whether they are already being corrected by the pilot or CADM actions. The failures to be corrected are ordered, and the system then attempts to <u>construct</u> a correction procedure (and its corresponding monitoring procedure). If successful, actions are taken and the success or failure of the procedure is monitored as new information is received. During all of these steps, information about CADM's actions is relayed to the pilot.

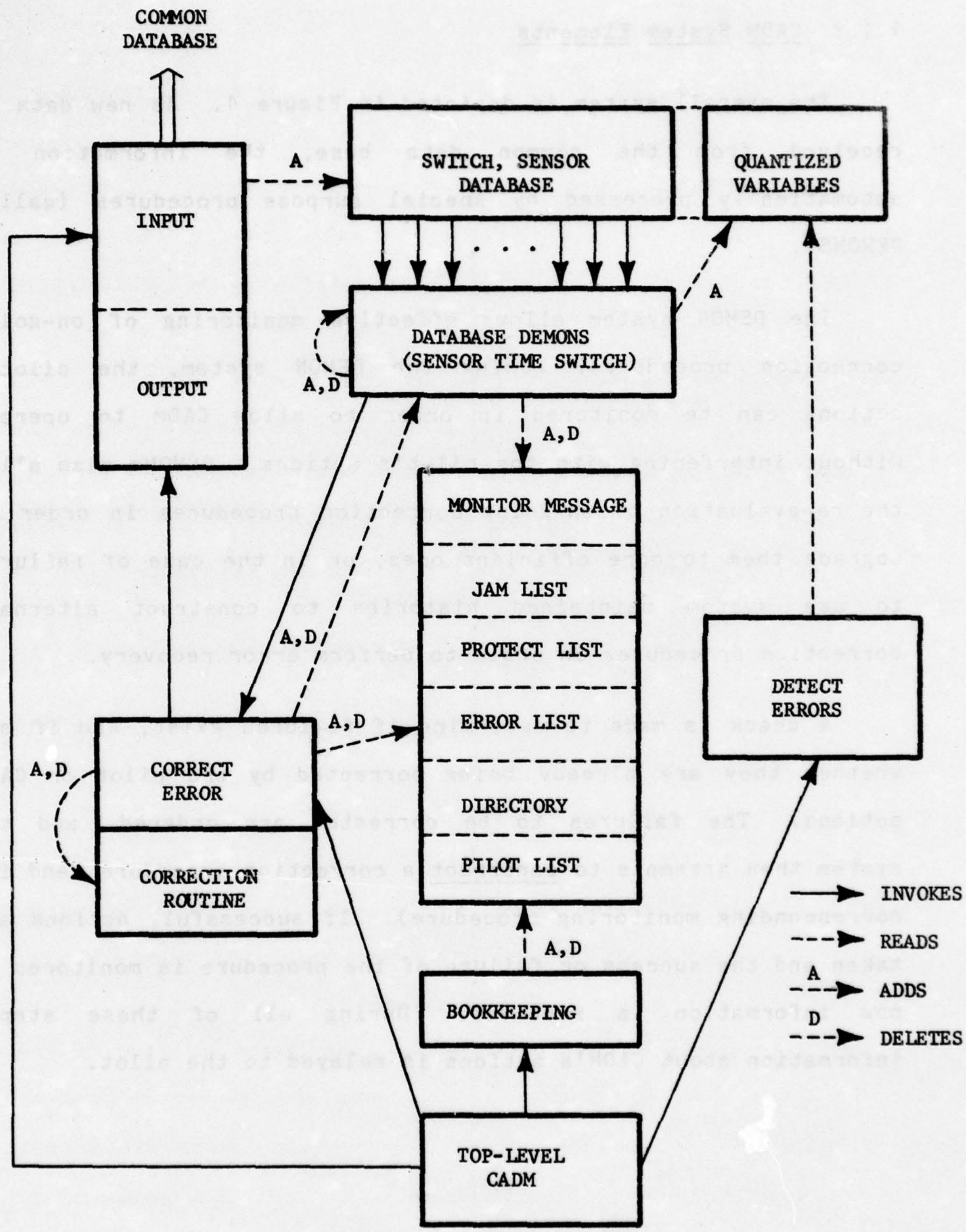

Figure 1. The CADM Software System.

1.2 Pilot-CADM Interaction

The effectiveness of a CADM in performing its functions, and consequently the viability of a mission itself, depends on the effectiveness of the interactions between CADM and the pilot. By sensing component malfunctions and failures of aircraft components, and subsequently effecting corrections or compensations for these malfunctions, CADM in fact relieves the pilot from having to make these corrections himself. This is a definite asset to the pilot engaged in combat or in other circumstances which demand his attention. On the other hand, CADM organizes information about its findings and its actions which it then can relay to the pilot on a visual display. The pilot can investigate further by requesting as much information as he desires. Any actions the pilot may take, however, cannot be countered by actions from CADM.

1.2.1 The Master Monitor Display

Information from CADM is displayed to the pilot on the Master Monitor Display (MMD). The information displayed is of two types, namely, general sensory and control status information, and information about CADM's activities.

1.2.1.1 The Display of Status Information

Because the amount of information available from the sensors, the controls, and CADM is very large, the information has been hierarchically organized for convenient display on the MMD [1,2]. Figure 2 shows a display on the MMD. The top two-thirds of the display is a page of data from the hierarchy. The pilot has a choice of six top level pages which display information about either the fuel, the electrical, the hydraulic or the engine subsystems, the flight plan or the failure monitor. Most of these top level data pages branch to other pages with more specific data. For example, the hydraulic data page has three branches to pages which display the pump system, the landing gear status, and the flap and wing sweeps. Data elements are intensified when they change, and thus attract the pilot's attention. After a short time with no change, the intensity is lowered.

The pilot uses a touchtone-like keyboard to choose data pages and branches. With so few keys, it is possible to learn how to perform without actually looking at the keyboard. Keyboard entries preceded by a control character select options on the multi-function display [3] which occupies the lower one-third of the MMD. The function currently in use is intensified for easy reference by the pilot. The multi-function display allows the pilot to put CADM into any of three modes: off, monitoring only, and on. In this way, he can easily override the CADM system.

FUEL TANKS

FRONT

9	FUEL QUANTITY	1000
8	DRAIN PUMP	OFF

REAR

7	FUEL QUANTITY	1000
6	DRAIN PUMP	OFF

5 FUEL PUMPS

VALVES

4	FRONT TO LEFT	OPEN
3	FRONT TO RIGHT	OPEN
2	REAR TO LEFT	OPEN
1	REAR TO RIGHT	OPEN

---

7 ENGINES	8 FLT PLN	9 FAILURE MON.
4 HYDRAULIC	5 ELECTRICAL	6 FUEL
1 CADM OFF	2 CADM DETECTING	3 CADM ON

Figure 2. The Master Monitor Display

1.2.1.2 The Display of CADM Activities

On the right side of each data page, status information indicates whether or not CADM has operated a particular control recently, and also indicates whenever a particular subsystem or component has failed. Messages concerning failures, along with their times of occurrence are displayed to the pilot at the bottom of the MMD. Table 1 summarizes the messages which CADM can send to the pilot. The pilot can access the corresponding data pages if he wishes more information concerning CADM's actions.

1.2.2 Pilot-to-CADM Communication

CADM must perform its functions subject to the actions of the pilot. In order to operate properly, CADM must be made aware that the pilot just closed a fuel valve, for instance, if it is to not undo that action while it attempts to correct, say, a fuel supply problem. In order to monitor the pilot's actions, a DEMON system is used by CADM. This DEMON system maintains a record of what equipment the pilot is currently using and when he last used it. In this manner, CADM is able to determine whether the pilot is using equipment which it has allocated for its own correction procedures. If the pilot is using such equipment, CADM can suspend the violated correction procedure and attempt to construct one which does not interfere with the pilot's actions.

Table 1. CADM Messages.

Number	Message
0	No Message (Blank)
1	Engine System Check
2	Fuel System Check
3	Electrical System Check
4	Hydraulic System Check
5	Left Engine Flameout
6	Right Engine Flameout
7	Left Engine Fire
8	Right Engine Fire
9	Left Engine Destroyed
10	Right Engine Destroyed
11	Buss Relay Open
12	Left Buss Down
13	Right Buss Down
14	Left Hydraulic Pump Failure
15	Right Hydraulic Pump Failure
16	Left Elec Fuel Pump Failure
17	Right Elec Fuel Pump Failure
18	Left Mech Fuel Pump Failure
19	Right Mech Fuel Pump Failure
20	Left Drain Pump Failure
21	Right Drain Pump Failure
22	Inadequate Hydraulic Pressure
23	Inadequate Hydraulic Fluid
24	Hydraulic Line valve Jam
25	Inadequate Fuel Flow to Left Engine
26	Inadequate Fuel Flow to Right Engine
27	Inadequate Fuel in Forward Tank
28	Inadequate Fuel in Rear Tank
29	Fuel Line Valve Jam
30	Intertank Flow Control Jam
31	Left Engine Temperature Low
32	Left Engine Temperature High
33	Right Engine Temperature Low
34	Right Engine Temperature High
35	Inadequate Left Engine Thrust
36	Inadequate Right Engine Thrust
37	Left Engine Vibration Irregular
38	Right Engine Vibration Irregular
39	Fuel Line Valve Jam (FT-LE)
40	Fuel Line Valve Jam (RT-RE)
41	Fuel Line Valve Jam (FT-RE)
42	Fuel Line Valve Jam (RT-LE)
43	Left Engine Restarted
44	Right Engine Restarted
45	Left Engine Fire Out
46	Right Engine Fire Out
47	Adequate Hydraulic Pressure
48	Adequate Fuel Flow to Left Engine
49	Adequate Fuel Flow to Right Engine
50	Left Engine Temperature Normal
51	Right Engine Temperature Normal
52	Left Engine Thrust Adequate
53	Right Engine Thrust Adequate
54	Left Engine Vibration Normal
55	Right Engine Vibration Normal

Although no attempt was made to endow CADM with the ability to determine the pilot's intentions, a preliminary study was made to determine whether it is feasible to make such an attempt in future computer aided decision making systems. This study was based on the following reasoning.

When flying an aircraft, a pilot has both control and monitoring tasks. When one of his monitoring tasks requires more attention than usual, it is expected that the pilot's control performance will be affected. Therefore, by inspecting the pilot's control performance, it should be possible to determine if his attention is directed to one of his monitoring tasks. With this information, CADM could possibly determine which monitoring task has attracted the pilot's attention, and then CADM can perform its actions without conflicting with the pilot's actions. The feasibility of such an approach could allow CADM to infer what the pilot is doing without explicitly asking him.

The aircraft situation was abstracted to include only a pursuit tracking task with randomly occurring arithmetic side tasks [4,5]. Subjects were instructed to minimize tracking error while solving the arithmetic problems without making multiplication errors.

The displayed tracking error and joystick outputs were monitored. A fading memory system identification algorithm [6,7] was employed to find the parameters of an N-th order sampled-data linear model of the pilot's tracking behavior. Through discriminant analysis [8] on these parameters, pure tracking and

tracking plus mental arithmetic modes were distinguished. It was then concluded that CADM could be profitably augmented by such a method for detecting the shifts of attention in a real time environment.

SECTION II

DEVELOPMENT OF THE CADM SYSTEM

It being the goal of this research to construct a prototype system which demonstrates the feasibility of computer aided decision making during inflight operations, the CADM system evolved through three phases of development. During the first phase, an analysis of flight operations was undertaken and tasks which the pilot performed were identified in order to define the functions of CADM [9]. During the second phase, CADM was implemented to perform several simple tasks during degraded mode operation of a simulated aircraft [10]. During the third phase, the task domain for CADM was enlarged to include the correction of complex failures brought about by the interdependence of various subsystems [11]. The final demonstration of the CADM showed its usefulness in degraded mode operation of aircraft [12]. In addition, the CADM system developed was demonstrated to be general with respect to aircraft types and extensiblty of its environment.

2.1 The CADM Problem Domain

In defining the problem domain for CADM, consideration was given to the tasks which the pilot must perform while in flight, in addition to the state of the art technologies for automating these tasks. In general, the pilot must control the aircraft and many of its subsystems; he must monitor the status of the

controls and the various subsystems; and he must attempt to correct failures or compensate for failures which result from malfunctioning components. Systems like the integrated information presentation and control system (IIPACS), developed at Boeing, advanced the concept that the pilot should be a system manager with the responsibility to make high-order decisions. IIPACS, however, did not succeed in decreasing the pilot's overall workload during critical times, although it did decrease his workload at non-critical times.

The pilot was presented with sensory information, failure detection information, fuel level status, etc., but he still had to perform most of the corrections himself.

Of the pilot's many tasks, most can be performed by brute force, number-crunching methods. However, tasks such as failure detection, prediction and correction, and degraded mode operation require intelligent assessment. Heuristic methods developed in the area of artificial intelligence can be applied in order to augment the pilot's capabilities with computer aided decision making. In addition, a form of intelligent intercourse between the pilot and a CADM system can enable CADM to relieve the pilot of an excessive workload.

2.2 The CADM System

In this light, CADM was presented as a system which performs failure detection and correction during degraded mode operation, and which works cooperatively with the pilot to maintain the safety of the aircraft in order to complete successful missions. To this end CADM was designed to seek alternative correction procedures when its proscribed actions are seen to interfere with the pilot's actions.

2.2.1 The Simulated Avionics System

In order to create a realistic environment for the development and testing of computer aided decision making system software, an integrated software model of the functions of an aircraft and its operating environment was written.

2.2.1.1 The Aircraft Model

The aircraft simulated is a single seat, twin jet, variable-geometry, fighter plane. The engines develop 15,000 pounds of thrust each, and the wings have five sweep settings. The flaps located on the trailing edges of the wings can be extended for wing sweep angles of 35 degrees or less. The landing gear have two positions, namely, fully extended and fully retracted.

The aerodynamics simulation programs simulate all aircraft motions except yaw and side force. Also, lateral motion is restricted to roll only. Inputs to the aerodynamic simulation come from the control stick, the throttles and the subsystem simulation.

2.2.1.2 <u>The Aircraft Subsystem Model</u>

The aircraft subsystem model (AIRSYS) is the primary work area for the CADM system. Through it the CADM can investigate and act on its environment. AIRSYS provides CADM with numerical data on various systems and components of the aircraft, and it allows the CADM alternatives for the correcting of a failure when a system or a subsystem malfunctions. The aircraft subsystems modeled in AIRSYS are the fuel/engine system, the electrical system and the hydraulic system.

2.2.1.2.1 <u>The Fuel/Engine System</u>

The fuel/engine system is composed of two engines, two fuel tanks, two drain pumps, one intertank pump, two engine driven fuel pumps, two electric fuel pumps, and four valves. The valve plumbing network allows one fuel tank to feed either or both engines. In addition, the system produces through the electrical system, sensor outputs and failure characteristics for the CADM to evaluate.

2.2.1.2.2 The Electrical System

The electrical system is composed of two engine driven generators, two fuel pumps, two hydraulic pumps, 48 circuit breakers, all sensors, and all valve actuators. Failures in this system are caused by the incorrect opening of the individual circuit breakers for the AIRSYS components.

2.2.1.2.3 The Hydraulic System

The hydraulic system is composed of one hydraulic fluid reservoir, two engine driven hydraulic pumps, two electrically driven hydraulic pumps, one accumulator pressure tank, eight valves, and the mechanisms for activating the wing sweep, the landing gear, and the flaps. Failures of components in this system can cause the landing gear, the flaps, and the wing sweep to be jammed in their current states. Also, the wing sweep can be jammed because of reduced hydraulic pressure in the accumulator pressure tank. Even with reduced pressure, however, the landing gear and flaps can still be operated hydraulically. Total system failure can result from the loss of the pumps, the loss of hydraulic pressure or the jamming of the valves.

2.2.2 The CADM Shared Data Base

The pilot, AIRSYS, and CADM all interact through a shared data base (SDB). In addition, a Gremlin routine can set failures in AIRSYS by operating on the SDB. All three AIRSYS systems are

heavily interconnected. Failures in one system could cause failures in another, thereby increasing the complexity of any correction scheme. Cooperation between the systems and the duplication of efforts offers the CADM and the pilot a number of alternatives when responding to a component failure, hence, making the possibility of total system failure more remote, and also increasing the complexity of the solution task.

2.2.3 <u>Hardware I/O for the Simulator</u>

The hardware of the simulator includes a joystick, two throttles, a touchtone keyboard to input and request data, a monitor display to display present AIRSYS states, and a vertical situation display (VSD).

The pilot utilizes the touchtone keyboard to input changes and corrections into AIRSYS. Through the keyboard, the pilot can change the wing sweep angle, the flap angle, and the gear state. He can also investigate or change the current state of any AIRSYS component and can correct a failure through the use of the appropriate code input to the keyboard.

The VSD displays aircraft pitch and bank angle on an artificial horizon. Heading is displayed on a compass. Altitude, airspeed, rate of climb, and command information are displayed on the VSD by means of bar graphs, alphanumeric symbols, and a moving aircraft symbol.

2.2.4 Programmed Intelligence for CADM

In order to achieve the capabilities stated earlier for CADM, artificial intelligence techniques were applied. Among the techniques used are pattern directed invocation of procedures, a DEMON system and CADM-generated special purpose procedures. The use of these techniques has allowed the implementation of a system with a flexible control structure in which new types of failure, detection and correction procedures can be easily added.

2.2.4.1 Control Structure Considerations for CADM

In order to allow CADM to operate in varying environments, the control structure was implemented in a manner which allows easy introduction of new failure types and corrective procedures. This flexibility allows CADM to alter its own correction procedures and failure detection criteria. As new types of failures such as jams are determined, corrective procedures dependent on the malfunctioning apparatus could be altered or removed.

Among the performance criteria which influenced the design of the control structure were:

1. The most important failures are to be attended to first. This necessitated the inclusion of a priority structure.
2. Without interfering with 1, an attempt should be made to correct errors in such a manner that internal conflict is minimized. When correcting two simultaneous failures, an attempt should be made to apply procedures which use different apparatus. This implies the need for a protection

mechanism to indicate and reserve equipment needs for the corrections.

3. The corrections generated by CADM should be methods which involve the least conflict with any pilot action. CADM tries to complement the pilot's actions rather than to compete with him for use of the available equipment.

4. As a consequence of 3, CADM must be able to recognize pilot actions and determine how these actions affect failures which have been corrected and are being monitored, as well as those that are presently being corrected.

2.2.4.2 Pattern Directed Invocation of Procedures

It is not practical to build a decision tree that incorporates all the possible combinations for all the failures. Operating with a more complicated airplane model would necessitate a great deal of rewriting to include new sensor combinations. Much of the flexibility is lost if the detection apparatus is in the form of a big flow chart. In order to overcome this, CADM's detection procedures are pattern-invoked. Associated with each procedure is a pattern, or template, which is a list composed of constants and variables. This means that a program can be called not only by name, but also whenever a datum element which matches the program's pattern is entered into the internal CADM database. A datum element representing a sensory input can directly invoke a program. Such a program is referred to as a DETECTION DEMON. Because of this feature, sensor reading data do not have to be checked needlessly. Furthermore, such pattern-invoked programs are easy to add into the program base

without disturbing the calling sequences and logic branches that already exist.

2.2.4.3 The DEMON System

DEMONs are employed to aid CADM with its failure detection and correction procedures. As mentioned above, a DETECTION DEMON can be evoked by the matching of a program pattern with a datum element entered into the CADM database. The same type of DETECTION DEMON structure is used to observe any pilot changes in valve or pump settings. If changes are found to have occurred, CADM can assess their relevance to failures being corrected and take appropriate action, such as suspending the correction.

When a failure is being corrected, CADM does not assume that, just because certain switch settings have been altered, the error no longer exists. Rather CADM waits to ensure that the expected response to the action occurs. However, in order to avoid remaining idle during this time, CADM monitoring procedures are constructed for each correction of a failure at the time of correction. A SUCCESS PREDICATE tests for a successful completion of the correction and a SUCCESS PROGRAM is executed when the correcton succeeds. Likewise, a FAIL PROGRAM is executed when the correction does not succeed.

These detection procedures are invoked after a certain amount of time has elapsed. New values of time invoke the particular monitoring procedure and, the pattern invoking

mechanism which was employed during detection of failures is also used. A MONITORING DEMON is created. The pattern contains a time variable and the body contains the monitoring procedure along with information to restrict the times when it can be invoked and reinvoked. When a MONITORING DEMON has served its purpose (either a success or a failure has been observed), it is removed from the system.

After the MONITORING DEMON has been created, an active list is updated to include the present failure, how the failure is being corrected and the name of the MONITORING DEMON which is monitoring the correction.

2.2.4.4 <u>CADM Generated Procedures</u>

CADM keeps an error list which contains all of the recently detected errors. In correcting failures CADM eliminates from this list those errors which are already being corrected. The entries are reordered so that the highest priority error will be corrected first. CADM maintains a list of all the error types that it recognizes, along with their relative priorities. This list can be altered by the program whenever new information indicates that the priorities should be changed. Whenever CADM corrects a failure, the first entry on the error list is examined and the relevant corrective routines are invoked. At this point, CADM cannot know which procedure will eventually be applied to correct the failure. It is aware only that a class of correction procedures exists. These procedures are collected into an

outline, called a CPROG, for each error type. This outline is used to determine in which order the individual procedures are examined. Each step in the outline represents a possible approach to correcting the problem. CADM searches the possibilities in order to find one which it judges to be appropriate.

A correction procedure is generally composed of three sections. In the first section CADM tests to see whether certain conditions exist among the various valves and pumps, for instance. If these conditions are not met, the procedure is deemed to be unsuitable and the next procedure is examined. In the second section CADM determines whether it is free to alter the desired apparatus. It does this by checking for jamming of the particular apparatus, conflicts with the pilot, and internal CADM conflicts. In the third section, when a procedure is found which CADM wishes to apply, the apparatus in question are reset. This activity has been monitored by a MONITORING DEMON which was constructed to ensure that the repair has progressed successfully.

If after examining all the possible procedures, a non-conflict solution is not found, CADM returns to those in which a conflict was found and tries to resolve the conflict.

2.2.4.5 <u>The Pilot-CADM Interface</u>

There were two considerations for the establishment of the Pilot-CADM interface. These were, first, the choice of the displays and controls, and second, the task allocation and the resolution of conflicts between the pilot and CADM.

2.2.4.5.1 The Displays and Controls

Hughes Master Monitor Display [1] was chosen for the displaying of failure detection information. For the purpose of CADM, however, several extensions were made to the MMD. Since CADM was demonstrated in conjunction with a simulated avionics system, the actual dials, gages, knobs, switches, etc., are not available for the pilot to observe and set. Thus, MMD was extended to include a "sensor" display and a "control" display as well as the "failure monitor" display.

2.2.4.5.2 <u>CADM Task Allocation and Conflict Resolution</u>

CADM's overriding concern is that the pilot must be able to maintain full control over the airplane's capabilities in order to successfully carry out the mission and, therefore, must not undo pilot actions. It monitors the pilots actions through the use of the DEMON system. A record is maintained of what equipment the pilot is using and when he last used it. With the DEMONs then, CADM can determine whether the pilot is using equipment which CADM has allocated for its own correction

procedures. If so, CADM can suspend the violated correction procedure, and try to construct one that does not interfere with the pilot's actions.

2.3 Advanced Features of CADM

Upon the completion of the second phase of development of CADM, the feasibility of a CADM system for performing simple tasks was demonstrated. The third phase of CADM development expanded this task domain to include multiple failure correction. In addition, CADM itself was made virtually airplane independent through improvements to its knowledge structure and through the implementation of routines which provide a history of the correction procedures which CADM attempts to effect.

2.3.1 Generalized CADM Correction Procedures

Because a goal of the CADM project is to investigate and develop a computer system which aids a pilot in carrying out missions, an attempt to make the CADM system as general as possible in its applications to different aircraft was undertaken. This means that the techniques used should not be geared to correcting a fixed class of errors on a fixed airplane type. To accomplish this, the system was augmented to introduce generality in two areas. First, the airplane model is treated as factual data rather than being explicitly coded into the program. Second, the correction procedures are generalized to model

component and instrument types rather than a specific switch or dial, with programmed knowledge of how these component types operate and affect the operation of the airplane.

In addition, the correction procedures were generalized. This was effected by the addition of two functions called MAKE and IS. The potentially relevant action procedures are generally associated with a component class. The system searches through the airplane model semantic net by use of the functions MAKE and IS. Basically, MAKE isolates action procedures and is used to construct correction procedures while IS is used to examine the state of the world to determine whether some condition is true or false for a group of components.

Whenever a MAKE call returns (at any level), several types of information are present:

1. A linear program segment (possibly NIL) indicating what steps and intermediate sensory checks should be made in order to bring about the desired results.
2. A structure called HISTORY summarizing the results of the construction effort. Also included in the history is information indicating why certain steps are in the plan segment, as well as what to do if a continuation of the search is necessary. This is used during error recovery.
3. Optional procedures indicating what to do upon successful completion or failure of the procedure. This may indicate such things as inferences which may be made or directions which should be pursued.

An IS call simply returns a HISTORY, possibly indicating which sensors were used to determine values.

2.3.2 Histories and Error Recovery

It is not reasonable for the system to assume that just because a possible correction procedure could be constructed, that the procedure will always be effective. Therefore, CADM has methods for constructing new and different procedures which take into account all new information as well as the knowledge of previously unsuccessful correction attempts. The structure called HISTORY performs this function.

The form of the HISTORY structure has four elements. The first element calls on MAKE to set a component, a component class or a sensor type to a desired state. The second element is a list of lists which indicate the current or expected state of the particular equipment being considered. The third element contains a list of relevant information such as histories or variables to be saved. The total information necessary to recreate the decision process can be obtained because each HISTORY can include an arbitrary number of histories. The final element of a HISTORY is a pointer indicating the continuation point of an ACTION procedure.

2.3.3 Multiple Failure Handling

Included among the class of multiple failures are those cases in which failures occur simultaneously, as well as those in which failures occur while CADM is monitoring the progress of on-going correction procedures. This involves CADM's overseeing the allocation or aircraft components. To do this, a variable priority structure relating the importance of correcting a class of failures to the mission profile and available equipment was implemented. While a correction is being made, all components which are to be used are allocated by the system to the correction procedure. The affected equipment is said to be protected. Pilot usage of components also causes protections to be instituted. Before any equipment is to be used, a check is made to ensure that no protection violations will occur.

Occasionally, a correction procedure for a failure will be constructed which is not the best possible (with respect to the expected speed of correction) but is the best available. This may be because the "better" equipment has been allocated for other purposes. In this system, the correction procedure which was determined would be initiated, but if the "better" equipment becomes available before the correction has been completed, the procedure would be re-evaluated to determine if it is possible to upgrade into one incorporating the "better" equipment.

SECTION III

THE SIGNIFICANCE OF CADM - AN OVERVIEW

Research is ultimately judged both within and without its specific academic and theoretical fields. This means that CADM will be judged not only by its theoretical richness within the field of artificial intelligence, but within more global contexts. In the USAF, the global context consists of the set of prevailing, current, and anticipated management and operational problems. In these contexts the evaluative criterion for research is simply, "Does this work address, offer insight into, or solve any aspect of my problems?"

A prevailing problem in the USAF has been the increasing life-cycle costs of avionics systems [12]. A major portion of these spiraling costs has been attributed to the avionics software. A costly deficiency in software procured by the USAF in the past has been the software's lack of flexibility. Typically the procurement of a new avionics system required the purchase of a unique, ground based support machine and the associated software for maintaining, translating code for, and interfacing with the on-board machine. The USAF operational environment (aircraft are dispersed over the world, the same avionics system is used in different types of aircraft, one aircraft may have several different avionics systems) has resulted from the purchase of many "unique" support machines and several flavors of support software for each new avionics system.

3.1 The Generality of CADM

The research accomplished during Phase 3 indicates that a portion of the problem of inflexibility need not be a future concern for the USAF. The CADM we have implemented is essentially airplane independent, i.e., the software is not written for any one specific airplane with a specific number of valves, pumps, engines, fuel tanks, electrical generators, etc. Once the host aircraft configuration is provided, CADM constructs a data structure representing the specific aircraft and uses this one-time computed structure in correcting failures and error conditions on that aircraft.

The CADM design philosophy provides flexibility in two dimensions: across types of airplanes, since the CADM correction procedures would work as well on a B-52 as on an F-15; and across time, since CADM can generate a new representative data structure as a result of modifications to existing aircraft*. Within these bounds, the presently implemented CADM is fully sufficient for handling any fuel and electrical power distribution system. This means that no additional software is required regardless of how such systems are configured. It also means that no conceptual extension is required (although more

*The degree to which this is possible is limited only by the degree to which CADM's model of the subsystem components (valves, pumps, etc.) is consistent with the actual aircraft components. The present CADM implementation models such components in a general, but somewhat idealized manner.

subsystem specific software is necessary) to provide sufficiency for handling any other subsystem which can be modeled as a network of discrete components.

3.1.1 <u>CADM Knowledge Structure</u>

Within the field of programmed intelligence, two primary criteria are used to determine how intelligent a particular program is, namely, the generality and the adaptability of the particular implementation. The previous discussion has revealed CADM to be highly general, using no specific aircraft dependent techniques. This high degree of generality is derived from two properties of the structure of CADM's store of knowledge. First, correction procedures are associated not with individual aircraft components but with classes of components, and second, aircraft subsystem error conditions are defined in terms of aircraft system parameters rather than in terms of component states.

CADM's knowledge is stored in a procedural net [13] which is a hybrid data structure resulting from the merging of a technique for producing a semantic net [14] and a technique for the procedural specification of knowledge [15].

3.1.2 <u>Hierarchies of System Component Classes</u>

In CADM, classes of aircraft subsystem components and specific components are nodes in a hierarchy. Links between the nodes are relations between the components and classes of

components. Procedures (programs) are associated with the most general nodes in a particular hierarchy (see Figure 3). This type of structure is suitable for modeling classes of components in the most general way. For example, the concept 'VALVE' is represented as being an entity that is between an engine and a tank. In our implementation all valves are electrically actuated. Hence, the concept 'VALVE' is subordinate to the concept 'ELECTRICAL INSTRUMENT'. Electrical instruments have switches to control them and circuit breakers to connect them to their source of power. Since the concept of an electrical instrument is very general, procedures to determine whether any electrical instrument is on or off (the switch must be on, the circuit breaker closed, and the power source active if the instrument is to be on) and procedures for turning any electrical instrument on or off are associated with the concept node 'ELECTRICAL INSTRUMENT'.

The advantage in this method is that a specific valve (e.g. VALVE37) only need have a pointer to the concept node 'VALVE' to inherit all the properties of valves. If more valves are added to an existing aircraft, the data structure representing the aircraft subsystem does not have to be completely reconfigured. Rather, one additional node and a pointer from that node to the concept node 'VALVE' is all that must be added to ensure that the added valves can be turned on and off*. There is no need for a

*Additional pointers must be added to the tanks and/or engines involved to ensure that the valves' functions in relation to the existing components are understood by the program.

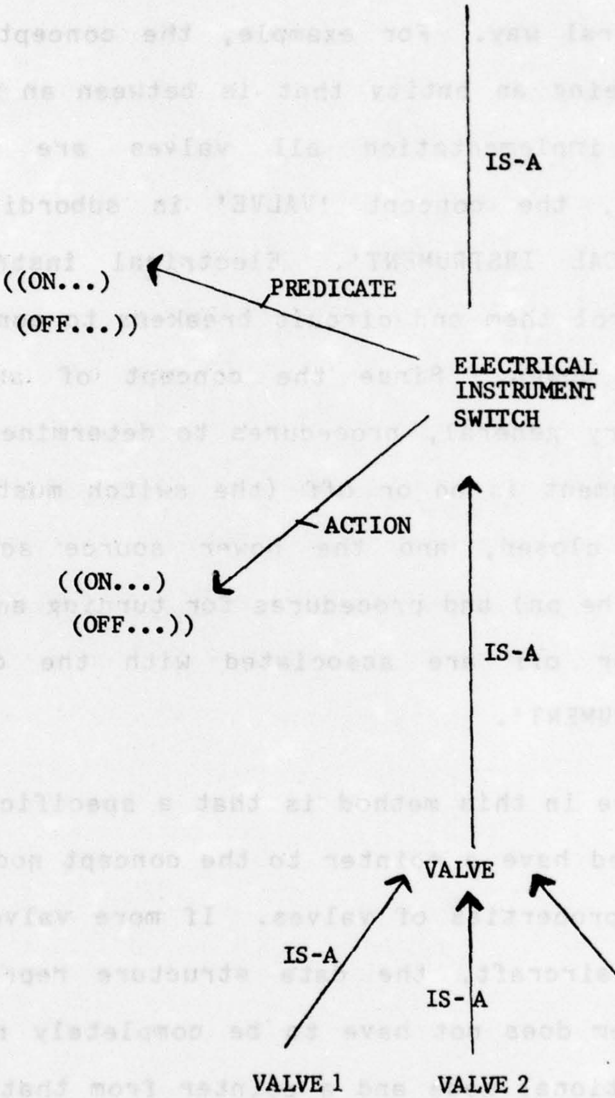

Figure 3. A hierarchy of procedures involving an electrical instrument.

specific procedure for controlling a specific valve (e.g. VALVE37). Of course, if VALVE37 is an unusual or special valve requiring a specific procedure to control it, that procedure can be associated directly with the node 'VALVE37', thereby preventing the more general valve control procedures from affecting VALVE37.

3.1.3 System Parametric Definitions of Failures

Equally important in providing CADM's generality is the definition of error conditions in terms of system parameters (engine temperature, fuel flow, etc.). This means that CADM does not have to continuously monitor the status of every individual component. This method of definition eliminates two problems. First, because the number of components in an aircraft is very large, continuously monitoring each component would consume much of the limited on-board computational capacity. Second, since there is usually considerable redundancy in aircraft systems, knowing the status of a particular component may convey little useful information by itself. An error condition is typically caused by improper relationships existing between several components rather than by the state of any one particular component.

Therefore, error conditions are defined by such entities as ENGINE TEMP LOW and INADEQUATE FUEL FLOW rather than by PUMP1 OFF or VALVE3 ON. This means that the correction procedures can be highly generalized specifications, as for instance, MAKE TEMP

NORMAL and MAKE FUEL FLOW POSITIVE, where TEMP NORMAL and FUEL FLOW POSITIVE are defined conditions. For example, FUEL FLOW POSITIVE requires fuel to be available from some tank, a valve between the tank and the appropriate engine to be open, and one of the fuel pumps to the appropriate engine to be on.

3.2 The Adaptability of CADM

The generalized structure of knowledge and the generalized definition of error conditions result in CADM's being a compensator rather than a diagnostician.

3.2.1 CADM's Role as an Operator

Because CADM is motivated to keep the aircraft flying rather than to determine exactly what caused the error condition, its performance is more that of an operator than of a maintainer. It is cognizant of the constraints of operating in real time. There are three distinct reasons for this. The first reason is that, in an operational aircraft, an error condition is a serious thing that needs correcting immediately. The first priority is to restore the aircraft's capability and the second priority is to identify what caused the problem and then repair it if possible.

The second reason is that CADM must cooperate with other intelligent entities. One of these entities is the pilot. If the pilot turns a particular valve, CADM assumes that the pilot has a good reason for doing so, even if closing the valve causes

an error condition. Consequently, rather than competing with the pilot and opening the same valve that the pilot just closed, CADM must compensate by finding another way to keep the aircraft flying, thereby preserving the pilot's independence. A second intelligent entity which CADM must deal with is CADM itself. CADM must be able to solve many problems simultaneously, i.e., multiple error conditions may occur simultaneously, may be detected simultaneously, and may require simultaneous correction. To accomplish this, CADM creates independent correction procedures, one for each error condition, and lets them operate concurrently. This means that there might be competition between two independent correction procedures for the same component. The losing procedure must find another way of accomplishing its goal even if the desired component is not available for use.

Finally, the third reason is that in our implementation the components are idealized and, with few exceptions (circuit breakers can become jammed open or closed), they cannot fail. Later versions of CADM will include non-idealized components and the capability to diagnose the fundamental cause of error conditions.

3.2.2 Adaptability Demonstrated by Program Response

Whereas generality is that property of a program design that ensures broad applicability of the program, adaptability is that property of a program that ensures stability of the program's performance within any one of its applications. In our

implementation, adaptability is demonstrated by the response of the program to perturbations in the composition of the aircraft system, to the pilot's desires, or to the failure of one of CADM's generated procedures to correct an error condition.

3.2.2.1 Responses to Failures

Consider the case when an aircraft engine is turned off in flight because it was damaged. An intelligent system would no longer expect FUEL FLOW POSITIVE to be desirable for the non-functioning engine. CADM recognizes FUEL FLOW POSITIVE into a damaged or destroyed engine as an error condition and corrects it in the same manner that it recognizes FUEL FLOW ZERO as an error condition into a healthy engine.

3.2.2.2 Responses to Pilot Intervention

In response to the pilot's desires, there are three available modes of CADM operation. Normally, CADM will be in a fully operational mode where it is detecting and correcting all error conditions. If for some reason the pilot does not desire CADM's assistance, he may completely disable CADM. In this situation, CADM becomes dormant, its second mode of operation, and is sensitive only to the pilot's call to return to duty. Finally, CADM may be placed in monitor mode where it detects error conditions and advises the pilot of them, but does nothing to correct them. These multiple modes have research as well as

operational implications. Such a capability is required if the performance of the man-machine combination in various situations is to be evaluated.

3.2.2.3 Responses to Correction Procedure Failures

A final example of CADM's intelligence and adaptability is its ability to cope with failure. If in the process of investigating an approach to correct an error condition CADM finds a method to be unfruitful, it provides as a continuation point for itself a data structure called a HISTORY. Using this HISTORY, CADM either may continue by investigating other methods within the same approach, or if the approach is found to be unsuccessful, it may try other alternate approaches. The important point is that CADM does not have to start all over again when a method or approach does not prove successful. It is able to make use of results of past efforts to solve the problem. Only after all approaches have proved ineffective does CADM pass the error condition to the pilot for correction.

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